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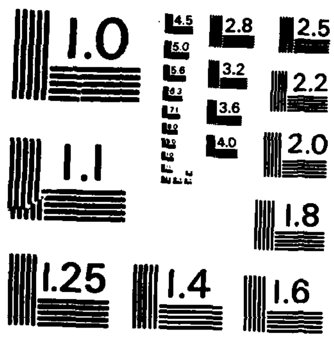

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This final report provides a review of the technical accomplishments and administrative highlights of the research program undertaken under ONR Contract N00014-82-K-0610, "Research with Nearfield Acoustic Holography." The main objective of the research was to characterize the potential and limitations of a new sound radiation and intensity vector field measurement technique in regard to both general theory and hardware application. The topics for study included: measurement system considerations (including array construction, data acquisition electronics, calibration of transducer elements, environmental effects, tests of the system accuracy, etc.), plane hologram data processing (including wrap-around error elimination, spatial resolution limits, zoom imaging, array processor algorithms, etc.), cylindrical and spherical data processing algorithms, wideband noise research, and holography for odd-shaped surfaces. The discovery of a technique for reconstructing radiation from odd-shaped surfaces represents a major breakthrough, as it allows the use of a plane array of transducers to image the backside of a three-dimensional object. Keywords →

This final report provides a review of the technical accomplishments and administrative highlights of the research program undertaken under ONR Grant N00014-82-K-0610, 'Research with Nearfield Acoustic Holography'. Most of the technical details of the research may be found in the publication 'Nearfield Acoustic Holography (NAH). I. Theory of Generalized Holography and the Development of NAH: [J. Acoust. Soc. Am. 78, 1395 (1985)] and in Appendix I of this report, which is a copy of the Ph.D. thesis of William A. Veronesi, 'Computational Methods in Nearfield Acoustic Holography'. The first part of this thesis has been submitted to the Journal of the Acoustical of America under the title 'Nearfield Acoustic Holography (NAH). II. Holographic Reconstruction Algorithms and Computer Implementation'; the second part will be submitted in the near future under the title 'Nearfield Acoustic Holographic Reconstruction of Low Symmetry, Odd-shaped Three-dimensional Sources'. This recent accomplishment represents a major breakthrough in the technique as it allows the use of a plane holographic array to image the backside of a three-dimensional object and permits depth resolution for cylindrical and spherical arrays beyond the corresponding level surfaces. The application of the research technology in the study of wideband noise radiation will be presented in the Ph.D. thesis of Donald J. Bowen, which is nearing completion, and will be submitted to the Journal of the Acoustical Society in the near future.

Following a statement of the scientific problem and theory of the technique, a brief review of each of the scientific accomplishments will be presented along with relevant publications and presentations.

Scientific Problem

An important area of acoustics is the measurement of the radiation of sound from a complex vibrating structure. A complete characterization of the sound generation and radiation requires a determination of the surface velocity and acoustic intensity of the structure, the farfield directivity pattern, the total acoustic power radiated, and most importantly the acoustic intensity vector field in the three-dimensional region surrounding the structure. The measurement of all of the necessary information for a high density of data points using conventional methods would be prohibitively time-consuming in nearly all instances and virtually impossible for wideband noise sources. The theory relevant to the problem is made difficult by the need for high spatial resolution and by the requirement of application to low symmetry, odd-shaped sources which do not coincide with the level surfaces of separable coordinate systems. The development of a sophisticated technique is indicated.

Technical Approach

A powerful technique, useful in many areas of measurement, is holography. With this technique, measurements made on a two dimensional surface may be used to reconstruct an entire three-dimensional wavefield. The great utility of holography arises from the enormous increase in the amount of information which occurs in going from a two-dimensional data set to a three-dimensional reconstruction. However, it is usually assumed in holography that the

resolution of a reconstructed image is limited by the wavelength of the radiation, and a large number of important sound radiation problems involve low frequency, long wavelength radiation. Because of this, acoustical holography had been rejected as a means of measuring low frequency sources. However the wavelength resolution limit is not intrinsic to the fundamental principles of holography but rather is due to experimental limitations which are always present in optical holography but are not necessarily present in acoustical holography. In our research we have developed a new technique called Nearfield Acoustic Holography (NAH) which suffers from none of the limitations of conventional holography and permits the determination of much more information than is usually associated from a holographic measurement. With the NAH technique a single measurement can be used to determine the source surface velocity, etc.; most importantly it yields the acoustic intensity vector field at a high density of points in the three-dimensional region surrounding the source.

Theory

Briefly, the holographic process involves representing the radiated wavefield as a superposition of eigenfunctions and using the data set measured on the two-dimensional surface to determine, as uniquely as possible, the coefficients of the superposition. The novel aspect of NAH is the inclusion of evanescent wave components which carry the high spatial frequency information but decay exponentionally with distance from the source. This theory is discussed in detail in the published review article mentioned above.

The analytic formulation of holographic reconstruction can be accomplished only for holograms recorded on the level surfaces of separable coordinate systems, and the holographic reconstruction can be continued only to the level surface which just touches the physical serface of the source. For low symmetry odd-shaped sources significant information is unobtainable, and the reconstruction may be said to lack 'depth resolution'. For odd-shaped surfaces the appropriate Green's function is not known analytically. However, for discrete holographic data sets and surfaces represented with finite element networks, the matrix equivalent of the Green's function may be found numerically. The problem here lies in the near lack of uniqueness and the strong dependence of the reconstructions on small changes in the input data. We have recently solved this problem with the use of the singular value decomposition method.

Goals and Accomplishments of the Research Program

The main objective of the research was to characterize the potential and limitations of the NAH technique in regard to both general theory and hardware application for a prototype planar holographic array. The topics for study included:

1. Measurement system considerations, including
   a. Array construction
   b. Data acquisition electronics
   c. Calibration of transducer elements
   d. Environmental effects (external noise, room reverberation, etc.)
   e. Tests of the system accuracy

2. Plane hologram data processing, including

   a. Wrap-around error elimination
   b. Spatial resolution limits
   c. Zoom imaging
   d. Array processor algorithms

3. Cylindrical and spherical data processing algorithms

4. Wideband noise research

5. Holography for odd-shaped surfaces

With the exception of the last two items, details of the topics have been published or submitted for publication. In the paragraphs below, a brief review of the accomplishments with reference to publications, papers, and lectures will be presented.

Early Work with the NAH System

When the importance of the evanescent wave components was first realized it was thought appropriate that the experimental feasibility of the technique should be tested. Research Associate E. G. Williams had just completed the construction of a microphone array for conventional acoustic holography, but when informed of the role of the evanescent waves he quickly realized the potential of the technique and readily modified the central section of the array which ultimately verified the enhanced resolution of the NAH technique. This success resulted in the publication:

> E. G. Williams, and J. D. Maynard, Phys. Rev. Lett. 45, 554-557 (1980) 'Holographic imaging without the wavelength resolution limit'

and in the submission of a patent disclosure. Subsequent reviews of the NAH technique based on the early work were published in:

J. D. Maynard and E. G. Williams, Proc. NOISE-CON 81, ed. L. H. Royster, E. D. Hart, and N. D. Stewart, (Noise Control Foundation, New York, 1981), pp. 19-24 'Nearfield holography, a new technique for noise radiation measurement'

E. G. Williams and J. D. Maynard, Proc. of the Int. Conf. on Recent Developments in Acoustic Intensity Measurement, ed. M. Crocker, et. al. (Centre Technique des Industries Mechaniques, Senlis, France, 1981) pp. 31-36 'Intensity vector field mapping with nearfield holography'

E. G. Williams and J. D. Maynard, Proc. of Inter-Noise 81, ed. V. M. A. Puetz and A. de Bruijn (Netherlands Acoustical Society, Delph, The Netherlands, 1981) pp. 1009-1012 'Intensity vector field mapping with nearfield holography'

J. D. Maynard and E. G. Williams, Proc. of Inter-Noise 82, ed. J. G. Seebold (Noise Control Foundation, New York, 1982) pp. 707-710 'Calibration and application of nearfield holography for intensity measurement'

Measurement System Considerations

The conventional holographic array built by Williams had too many features inappropriate for NAH and it was decided to build an entirely new array. The new array incorporated significant improvements in the following areas:

Construction

1. The microphones are small electret transducers with built-in FET impedance converters. They are plugged directly into small circuits which each have two amplifiers, a gain select network, a low pass filter, and a multiplexing switch. The circuits are mounted to a highly transparent wire lattice support system, which produces minimum disturbance of the sound field to be measured. With the on-site multiplexing only 32, rather than 256, cables are required to carry signals from the 16x16 microphone array.

2. In the early system data points for monotonal sources were interspersed by translating the source by hand. This was tedious and introduced errors due to changing standing wave patterns in the quasi-anechoic room. In the new system the highly transparent array is translated resulting in minimum perturbation of the sound field; the translation is under computer control so that the operator need not even be present during data acquisition.

Data Acquisition

The new array has a very high speed computer controlled switching system so that measurements can be made on uncontrolled wideband noise sources. A difficulty arises in trying to maintain accurate analog signals from the microphones in the presence of the high speed digital switching transients. Overcoming this difficulty was a major technical accomplishment achieved by graduate student D. J. Bowen; this will be discussed in detail in his Ph.D. thesis.

Calibration of the array elements

As found for other acoustic intensity measurement systems, microphone calibration is crucial. However it is less crucial in NAH because one has the statistical advantage of a large number of data points. By eliminating the eigenfunctions most sensitive to error, the hologram overdetermines the source, and errors in calibration are averaged out. To maximize the accuracy of our array for research purposes we developed our own sealed bellows calibration system, with a reference Bruel and Kjaer microphone, for calibration of the array microphones in situ.

Environment

In order to eliminate a health hazard, the fiberglas panels forming the anechoic chamber around the microphone array have been replaced with acoustic foam wedges. The major external noise source was the on-line minicomputer, which had to be sealed in an air-tight enclosure to minimize its sound radiation. From a technical point of view, the NAH technique is insensitive to standing waves and external noise , since the holographic technique can easily distinguish between real and image sources. A more serious problem arises from 'digital images' in the wrap-around error discussed below.

Tests of the system accuracy

The accuracy of the microphone array calibration was tested in two ways. In one test the holographically reconstructed surface velocity of a rectangular plate vibrating in a normal mode was compared to the results obtained by (tedious) point-by-point accelerometer measurements. The velocity represents a stringent test because it is essentially determined from a derivative of the hologram data which magnifies any errors. The second test involved comparing all reconstruction properties with those predicted for a theoretically tractable source: an unbaffled uniformly oscillating disk. The major problems here were writing the computer programs to obtain the non-trivial theoretical predictions, and to experimentally realize a true uniformly oscillating (rigid) disk. These tests indicated that the NAH technique was accurate to one or two dB. The tests of the NAH calibration are reported in two Master's theses:

William Y. Strong, M.S. thesis 'Experimental method to measure low frequency sound radiation - Nearfield Acoustic Holography'

T. D. Beyer, M.S. thesis, 'Test of the Nearfield Acoustic Holography technique using an unbaffled uniformly oscillating disk'

Plane hologram processing

In our research with NAH, the main data processing considerations were speed and accuracy, given reasonably good experimental conditions. It was found that the following items were most important:

Enhancement with a dedicated array processor

In order to determine an intensity vector field map, the sound pressure and three components of the particle velocity must be reconstructed at typically 50,000 points in space. For wideband sources this processing must be repeated for each temporal frequency component of interest. To expedite single frequency processing and to make wideband processing feasible a dedicated array processor is essential, and a CDA MSP-3000 was added to the Penn State NAH system. The array processor not only accelerates the temporal and two-dimensional spatial FFT's by a factor of 60, it also has array manipulation features which speed-up the calculation of the Green's functions, window functions, hidden-line graphic output, etc. A significant part of our research has been to find the best time-efficient alogrithms for the array processor.

Wrap-around error

In the course of using the NAH computer algorithms to study data obtained in another (underwater) acoustics experiment, the severity of a problem known as the wrap-around error became apparent. This error is a result of the finite and discrete nature of the hologram data recording and processing. There are a number of data processing methods which might be used to minimize the error, and a part of our research has been devoted to finding the best method. The importance of the wrap-around error and its treatment were first discussed in:

R. L. Ochs, J. D. Maynard, E. G. Williams, and J. W. Hughes, J. Acoust. Soc. Am. 74, 1572-1576 (1983) 'The extreme nearfield of an acoustic diffraction grating'

An interim method for treating the wrap-around error was published in:

E. G. Williams and J. D. Maynard, J. Acoust. Soc. Am. 72, 2020-2030 (1982) 'Numerical evaluation of the Helmholz integral for planar radiators using the FFT'

A thorough description of the wrap-around problem and its significance may be found in the published review article in the J. Acoust. Soc. Am. mentioned in the introduction. In our subsequent research better methods for treating the problem have been discovered. Details of the improved and tested reconstruction algorithms may be found in:

W. A. Veronesi and J. D. Maynard, submitted to the J. Acoust. Soc. Am., 'Nearfield acoustic holography (NAH). II. Holographic reconstruction algorithms and computer implementation'

W. A. Veronesi, Ph.D. degree, January 1985, 'Computational methods in Nearfield Acoustic Holography'(Appended to this report)

Spatial resolution

As discussed in the introduction the fundamental feature of NAH is the enhanced spatial resolution. The principles and theory of the resolution of holography and NAH are discussed in the review in the J. Acoust. Soc. Am. In an experimental test of the spatial resolution,

two simple sources radiating with a 3m wavelength were resolved to within a few centimeters, corresponding to an enhancement in resolution beyond the wavelength limit of two orders of magnitude. In practice the resolution is limited by the size of the transducers and the distance from the source.

Zoom Imaging

A number of the quantities of interest which may be determined from the hologram data are evaluated in the far field. It is usually desirable to examine such quantities over an area which is much larger than the original hologram aperture, but extending the aperture size using the normal holographic reconstruction algorithms would necessitate prohibitively long computation times. However, the farfield includes no evanescent wave components, so that processing need be applied only inside the radiation circle. We have developed a fast computer algorithm which enhances the density of data points inside the radiation circle and greatly magnifies the size of the aperture in the farfield. This technique is referred to as zoom imaging. Details will be presented in the future Ph.D. thesis of Y. Huang.

Cylindrical and Spherical Coordinate Holography

The theory for nearfield holography in cylindrical and spherical coordinates turned out to be quite straightfoward; the theory is presented in the review in the J. Acoust. Soc. Am. The technique merely involves the evaluation of various Hankel and Bessel functions

for the Green's function. However, the use of these coordinate systems with holographic reconstruction is still limited to sources with exact cylindrical or spherical symmetry; the problem of depth resolution for odd-shaped sources remains. Because practical applications of holography would require reconstructions of odd-shaped sources, it was decided to concentrate our efforts on the development of a new technique which was not restricted to exactly planar, cylindrical, or spherical sources.

Wideband Noise Research

One of the major discoveries which resulted from the initial application of NAH was the observation of circulating acoustic energy flow fields, i.e. regions in the acoustic intensity vector field in the nearfield of a source which form circular patterns. Sources generating such fields would have regions of large intensity magnitude but would radiate relatively little total acoustic energy into the farfield. These circulating patterns were ubiquitous for monotonal low frequency sources, and it was believed that the effect was a result of the high degree of temporal and spatial correlation which is possible with a structure vibrating at a single frequency. It is an interesting question as to what happens to the circulating energy flow fields for a wideband noise source when the temporal and spatial correlation is degraded, and this question was selected as the initial test problem for the wideband noise NAH system. The experimental test source for this problem was a rigid baffle containing two 30cm diameter pistons; this source was selected because its sound radiation properties may be

calculated exactly and compared with the experimental results, thus providing a test of the NAH system for wideband noise. A computer controlled multichannel noise synthesyzer was constructed for driving the the two pistons independently with a set amount of temporal correlation. The ratio of the radiated wavelengths to the piston size and separation provided a particular degree of spatial correlation. To date several notebooks of data have been collected with the pistons being driven under a wide variety of conditions. At the present time the data is being systematically examined for relationships between the temporal and spatial correlation and the acoustic intensity vector field patterns and the total sound power radiated. The results of this research, together with a detailed description of the NAH wideband noise system, will be presented in:

D. J. Bowen, Ph.D. degree (nearing completion) 'Nearfield Acoustic Holography for wideband noise sources'

Holography for Odd-shaped Surfaces

As discussed in the introductory theory section, the current NAH technique can reconstruct the acoustic field up to the plane, cylindrical, or spherical surface which just touches the physical boundary of the vibrating structure. In order to reconstruct the field up to the surface of an odd-shaped source, it is necessary to know the particular Green's function (not the free space Green's function) which satisfies a homogeneous boundary condition at the surface of the source. While a formal mathematical procedure may be established, the difficulty lies in the numerical execution of the procedure. Briefly, the problem is that any vibrator may have modes which radiate very

weakly into the hologram surface, and any slight errors in the hologram may reconstruct as large amplitudes at the surface of the source; that is, the inverse propagator may have 'singularities' which correspond to division by a quantity (a foward propagation amplitude) which is nearly zero. The solution to the problem lies in identifying the most singular modes and discriminating against them for the reason that they would require unrealistic amplitudes at the surface of the source. This is another way of viewing the treatment of the evanescent wave components and the finite dynamic range of the recording medium in the current NAH technique. For source surfaces which are level surfaces of separable coordinate systems the singular modes are already identified and treated in the data processing algorithms, but for a general source surface the singular modes are not known. Complicating the problem further are the interior resonance modes for the particular surface.

Recently we have developed a numerical technique which determines the Green's function for an odd-shaped source, isolates the interior resonances and the most singular radiating modes, and reconstructs the surface and radiated fields from a hologram data set. The technique uses a powerful operation in numerical linear equation theory known as singular value decomposition. With this technique a planar hologram may be used to reconstruct the backside of a three-dimensional source. This is possible because the correct Green's function accounts for diffraction around the surface of the source. The details of the technique are presented in the second half of the appendix to this report.

Miscellaneous accomplishments

The research with the NAH system has resulted in many lectures, presentations, etc. These include:

Patent for Nearfield Acoustic Holography (No. 4,415,996) awarded November 1983

Papers presented at Acoustical Society meetings

W. A. Veronesi and J. D. Maynard, J. Acoust. Soc. Am. 75, S71 (1984) 'Advances in Nearfield Acoustic Holography algorithms I. Green's functions'

Yanmin Huang, W. A. Veronesi, and J. D. Maynard, J. Acoust. Soc. Am. 75, S71 (1984) 'Advances in Nearfield Acoustic Holography algorithms II. Zoom imaging'

Youngchun Lee and J. D. Maynard, J. Acoust. Soc. Am. 75, S71 (1984) 'The implementation of Nearfield Acoustical Holography with an array processor'

Youngchun Lee and J. D. Maynard, J. Acoust. Soc. Am. 75, S71 (1984) 'Experimental studies of acoustic radiation from complex planar sources with nearfield holography'

D. J. Bowen and J. D. Maynard, J. Acoust. Soc. Am. 75, S71 (1984) 'Nearfield Holography for wideband sources'

W. A. Veronesi and J. D. Maynard, J. Acoust. Soc. Am. 75, S71 (1984) 'Holographic reconstruction of odd-shaped 3-D sources'

Invited lectures:

Colloquium, University of Michigan, Ann Arbor, Department of Physics 'Sound radiation measurement with Nearfield Holography'

Symposium, 104th Meeting of the Acoustical Society of America, Orlando, Florida 'Sound radiation measurement with Nearfield Holography'

Colloquium, S.U.N.Y., Buffalo, Department of Physics, 'Nearfield Holography and the Acoustic Vortex'

Plenary Session, 106th Meeting of the Acoustical Society of America, San Diego 'Nearfield Acoustical Holography techniques used to visualize radiated sound fields'

Colloquium, Lehigh University, Department of Physics 'Nearfield Holography and the acoustic vortex'

Colloquium, Amoco Production Laboratory, Tulsa, Oklahoma
'Nearfield Acoustical Holography'

Symposium, 108th Meeting of the Acoustical Society of America, Minneapolis 'The use of motion picture graphics in acoustics'

Seminar, Laboratory for Atomic and Solid State Physics, Cornell University 'Various acoustic and low temperature experiments at Penn State'

Major reviews of NAH including theory, measurement system construction, and fundamentals of data processing:

J. D. Maynard, in Frontiers of Physical Acoustics: International School of Physics "Enrico Fermi" XCII Course, ed. D. Sette (North Holland/Elsevier, New York, 1985) 'Nearfield acoustic holography'

J. D. Maynard, E. G. Williams, and Y. Lee, J. Acoust. Soc. Am. 78, 1395 (1985) 'Nearfield acoustic holography (NAH). I. Theory of generalized holography and the development of NAH'

Other publications based on the most recent work with the wideband noise NAH system and the reconstruction technique are forthcoming.

END

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